Quasielastic 1p-shell Proton Knockout from ^{16}O at $Q^2 = 0.8$ (GeV/c)^2

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In Hall A, Jefferson Laboratory, we have measured the cross sections for 1p-shell proton knockout in ^{16}O(e, e′p) reaction at $\omega = 439$ MeV and $Q^2 = 0.8$ (GeV/c)^2 for $P_{miss} \leq 355$ MeV/c. The response functions R_{L+TT}, R_T, R_{LT}, and the left-right asymmetry A_{LT} have been extracted for the $1p_{1/2}$ and the $1p_{3/2}$ states. For $P_{miss} < 280$ MeV/c, the data are all well described by DWIA calculations. This is in contrast to some previous measurements at lower Q^2. At large missing momentum, we have observed structure in left-right asymmetry, which qualitatively indicates existence of relativistic effects.

Quasielastic (e, e′p) provides a powerful probe of electromagnetic properties of proton and proton momentum distributions in nuclei [1]. In the Impulse Approximation (IA), the proton absorbs the virtual photon emitted by the incident electron and interacts with the rest of the nucleus as it emerges. The final state interaction (FSI) between the knocked-out proton and the residual nucleus is usually described by an optical potential derived from fits to existing proton-nucleus scattering data. Meson exchange currents (MEC) and isobar currents (IC) also contribute to this process. At high Q^2, quasielastic (e, e′p) is expected to be dominated by one-body current, however, relativistic effetcs start to play a role. Calculations show that the longitudinal-transverse response function R_{LT} and left-right asymmetry A_{LT} are sensitive the relativistic effects [2] [3].

In the one photon exchange approximation, the fivefold cross section for ^{16}O(e, e′p) $1p$-shell proton knockout can be written as $d^5\sigma/d\omega d\Omega_e d\Omega_p = K\sigma_{Mott}\ (V_L R_L + V_T R_T + V_{LT} R_{LT}\cos\phi + V_{TT} R_{TT}\cos(2\phi))$, where $K = E_p p_p/(2\pi)^3$, σ_{Mott} is the Mott cross section, $V_L = \frac{Q^4}{\vec{q}^{\,4}}$, $V_T = \frac{Q^2}{2\vec{q}^{\,2}} + \tan^2(\theta_e/2)$, $V_{LT} = \frac{Q^2}{\vec{q}^{\,2}}[\frac{Q^2}{\vec{q}^{\,2}} + \tan^2(\theta_e/2)]^{\frac{1}{2}}$, and $V_{TT} = \frac{Q^2}{2\vec{q}^{\,2}}$ are kinematic factors, and ϕ is the out-of-plane angle. ω and $\vec{q}$ are the energy and momentum transfer respectively, and $Q^2 = \vec{q}^{\,2} - \omega^2$. Missing energy and missing momentum are defined as $E_{miss} = \omega - T_p - T_R$ and $\vec{P}_{miss} = \vec{p}_p - \vec{q}$, where $\vec{p}_p$ and T_p are the momentum and kinetic energy of the knocked-out proton, and T_R is the kinetic energy of the recoil nucleus. The response functions R_L, R_T, R_{LT}, and R_{TT} contain all the information about the nuclear electromagnetic current. R_{LT} can be obtained by measuring the cross sections on both sides of $\vec{q}$ ($\phi = 0^\circ$ and $\phi = 180^\circ$) with ω, Q^2, and P_{miss} fixed. By combining the cross section measured at a different beam energy but the same ω, Q^2, and P_{miss}, the response functions $R_L + \frac{V_{TT}}{V_L} R_{TT}$ and R_T can be separated. For the kinematics of this expriment, $R_{TT} \ll R_L$.

^{16}O(e, e′p) $1p$-shell proton knockout experiments have been performed at NIKHEF [4] [5], Saclay [6], and Mainz [7] only at low Q^2 in various kinematics. Inconsistencies in these data have been found when comparing them to standard Distorted Wave Implse Approximation (DWIA) calculations. The DWIA calculation using the spectroscopic factors and parameters for the bound state wave functions extracted from fits to the data of Leuschner *et al.* [4] at NIKHEF overestimates the distorted momentum distribution measured by Blomqvist *et al.* [7] at Mainz by almost a factor of two even at low missing momentum. Further, the response function R_{LT} measured by Chinitz *et al.* [6] and Spaltro *et al.* [5] agree reasonably for the $1p_{1/2}$ state but disagree dramatically for the $1p_{3/2}$ state. These inconsistencies indicate the deficiencies in standard DWIA calculations. Experiment E89-003 [9] [10], recently performed in Hall A at Jefferson Laboratory measured the cross sections and separated the response functions R_{L+TT}, R_T, and R_{LT} for $1p$-shell proton knockout at $Q^2 = 0.8$ (GeV/c)^2. This data set clarifies some of the discrepancies in the previous experimental work and tests the dynamical and kinematical relativistic effects in the DWIA calculations.

E89-003 used the standard Hall A setup, two high resolution spectrometers (HRSE and HRSH) to detect electrons and protons respectively. At the focal plane of each spectrometer, two scintillator planes provide trigger signal and time-of-flight (TOF) information, and two Vertical Drift Chambers (VDCs) are paired to precisely locate the trajectories of the charged particles. In addition, a CO_2 gas Cerenkov detector located on HRSE can separate electrons from π^-. A three-foil waterfall target was used. The thickness of each foil along the beamline was about 130 mg/cm^2, and the typical 100% duty factor beam current was $\sim$70 μA. The optical properties [11] [12] and acceptance [13] of the spectrometers were studied carefully. Because quasielastic kinematics was chosen, H(e, e′) was used as a continuous luminosity monitor, and H(e, e′p) was used to determine the $\vec{q}$-direction precisely. The kinematics of this experiment were fixed at $\omega = 439$ MeV, $Q^2 = 0.8$ (GeV/c)^2, and $T_p = 0.427$ GeV. Missing momentum distributions were investigated by changing the angle between $\vec{q}$ and the HRSH. As $\vec{q}$ and $\vec{p}_p$ had nearly the same magnitude, and the angle between them was small, missing momentum was about perpendicular to $\vec{q}$. Three beam energies (0.843 GeV, 1.643 GeV, and 2.442 GeV) were employed to separate the response functions. For $E_{beam} = 2.442$ GeV, data were taken at $\theta_{pq} = 0^\circ, \pm 2.5^\circ \pm 8^\circ, \pm 16^\circ$, and $\pm 20^\circ$, while for $E_{beam} = 0.843$ GeV data were taken at $\theta_{pq} = 0^\circ, +8^\circ$ and $+16^\circ$. The data taken at $E_{beam} = 1.643$ GeV with $\theta_{pq} = 0^\circ, \pm 8^\circ$ were for systematic checking. In fact, for $\theta_{pq} = \pm 8^\circ$, R_{LT} and A_{LT} extracted at $E_{beam} = 2.442$ GeV agree with those extracted from $E_{beam} = 1.643$ GeV within one standard deviation. The overall systematic error in the extracted response functions was estimated to be about 5%. It was dominated by the uncertainty of H(e, e′) cross section to which the data were normalized.

Figure 1 shows the radiatively corrected ^{16}O(e, e′p)

missing energy spectrum with $E_{beam} = 2.442$ GeV at 45 MeV/c missing momentum. The two prominent peaks at 12.1 MeV and 18.4 MeV missing energy correspond to proton knocked-out from $1p_{1/2}$ and $1p_{3/2}$ states of ^{16}O. The missing energy resolution (FWHM) is about 0.9 MeV. The broad pump peaked at missing energy of 42 MeV is due to proton knockout from $1s_{1/2}$ state. The spectroscopic factor of $1s_{1/2}$ obtained by fitting a DWIA calculation with the energy dependent Lorentzian parametrization [14] folded in is about 88%. The strength of the $(2s_{1/2}, 1d_{5/2})$ doublet (peaked at missing energy 17.4 MeV) is expected to be small for this kinematical region and has not been removed from the $1p_{3/2}$ state data during the analysis.

Figure 2 shows a comparison between the measured cross sections and the relativistic DWIA calculations from Kelly [2] [15] and Van Orden [16] [17] [18] [19]. The spectroscopic factors of calculations from Van Orden are (0.61,0.67) for $(1p_{1/2}, 1p_{3/2})$ states. The data is in good agreement with both DWIA calculations for missing momentum less than 280 MeV/c. At higher missing momentum, there is some discrepancy between the data and the calculations. By using calculations from Kelly, the spectroscopic factors of the previous data sets are summarized in Table I

	Kinematics	$1p_{1/2}$	$1p_{3/2}$
Blomqvist	$x \sim 0.66$, $T_p \sim 196$ MeV		
Chinitz	$x \sim 0.89$, $T_p \sim 160$ MeV		
Gao	$x \sim 0.97$, $T_p \sim 427$ MeV	0.75	0.64
Leuschner	$0.08 < x < 1.5$, $T_p \sim 96$ MeV	0.75	0.64
Spaltro	$x \sim 1.03$, $T_p \sim 84$ MeV		

TABLE I. Spectroscopic factors for existing data

Figure 3 shows a comparison between the extracted left-right asymmetry ($A_{LT} = \frac{\sigma(\phi=0^\circ)-\sigma(\phi=180^\circ)}{\sigma(\phi=0^\circ)+\sigma(\phi=180^\circ)}$) and the DWIA calculations. At missing momentum less than 200 MeV/c, the data basically agree with both relativisitc and non-relativistic DWIA calculations. At larger missing momentum, A_{LT} from different calculations diverge : the relativistic DWIA calculations from Kelly [2], Udias [3], and Van Orden [16] [17] [18] [19] all predict the existence of a wiggle in A_{LT}; while in the non-relativistic DWIA calculations of Kelly, A_{LT} keeps going down. Data qualitatively agree with the relativistic calculations. The relativistic effects at high missing momentum are mainly due to dynamical enhancement of lower components of Dirac spinors in bound state wave functions, and the shape as well as the magnitute of the wiggle are very sensitive to the final state interactions [2].

Figure 4 shows a comparison of the response functions R_L, R_{LT}, and R_T with the DWIA calculations. The data are reasonably consistent with both DWIA calculations. Since the DWIA calculations of Kelly can describe the R_{LT} for $1p_{3/2}$ state measured by Chinitz *et al.* [6] but underestimate the R_{LT} for $1p_{3/2}$ state measured by Spaltro *et al.* [5], the consistency between the calculations of Kelly and the R_{LT} measurement from this experiment indicates that this data set agrees with that of Chinitz *et al.* [6] but disagrees with that of Spaltro *et al.* [5]

In summary, cross sections as well as response functions R_L, R_{LT}, and R_T for ^{16}O(e, e′p) $1p$-shell proton knockout have been precisely measured at $\omega = 439$ MeV and $Q^2 = 0.8$ (GeV/c)^2 up to 355 MeV/c in missing momentum. This is the first data set of ^{16}O(e, e′p) at such high Q^2. At missing momentum less than 200 MeV/c, the data are in reasonably good agreement with the DWIA calculations. At higher missing momentum, structure in A_{LT} has been observed, which is qualitatively consistent with the prediction of relativistic DWIA calculations. By using the DWIA calculations from Kelly, this data set agrees with the data of Leuschner *et al.* [4] and Chinitz *et al.* [6] but disagree with those of Spaltro *et al.* [5] and Blomqvist *et al.* [7]

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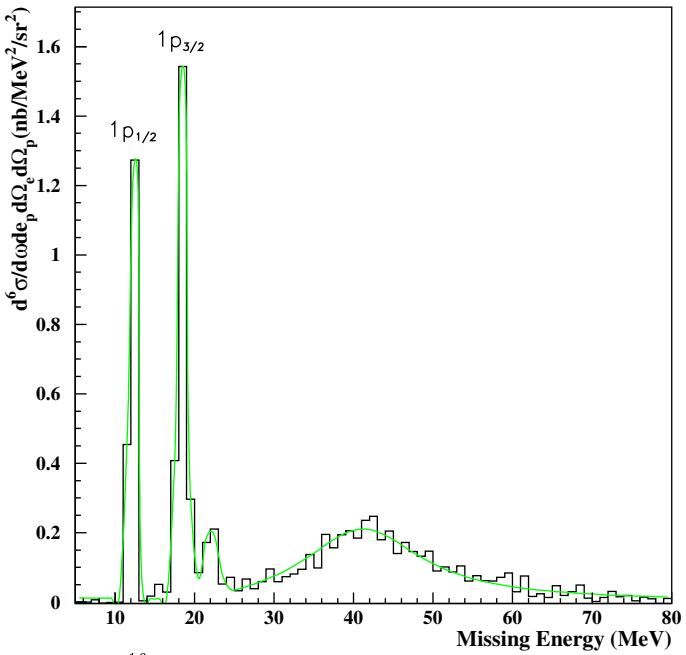

FIG. 1. ^{16}O(e, e′p) missing energy spectrum for 2441.6 MeV beam energy at $\theta_{pq} = +8°$. The $1p_{1/2}$ and $1p_{3/2}$ states are clearly visible. The FWHM missing momentum resolution is ∼0.9 MeV.

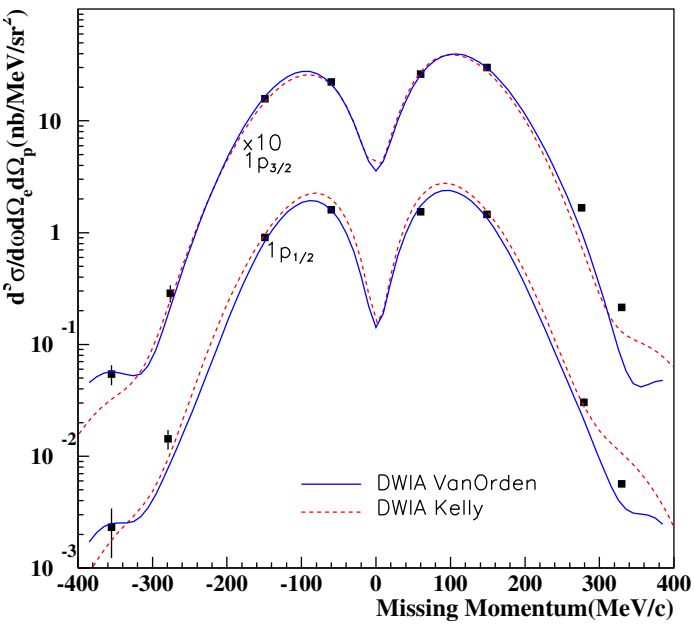

FIG. 2. Comparison of the cross sections with the DWIA calculations. The beam energy is 2.442 GeV. Both DWIA calculations describe the data very well.

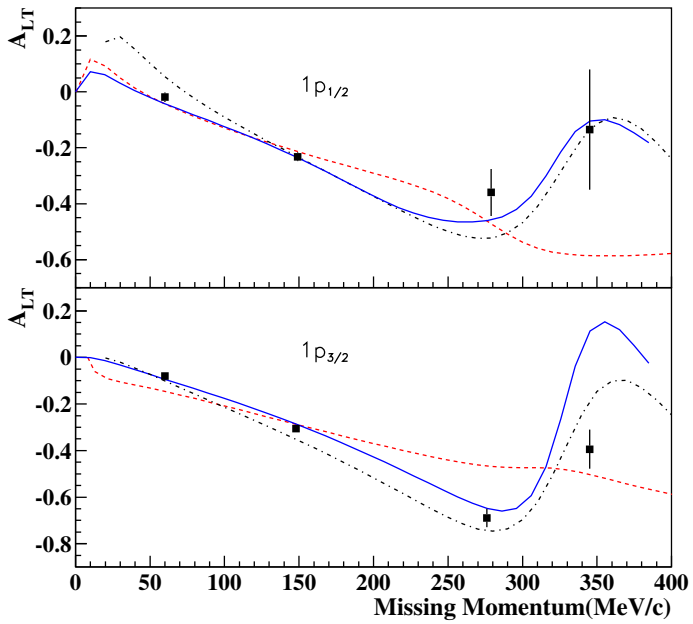

FIG. 3. Comparison of the left-right asymmetry with the DWIA calculations. The beam energy is 2441.6 MeV. The dashed line is DWIA from Kelly [2] with spinor distortion, dotted line is from Kelly [2] without spinor distortion, the dash-dotted line is DWIA from Udias [3], and the solid line is DWIA from Van Orden [16] [17] [18] [19] .

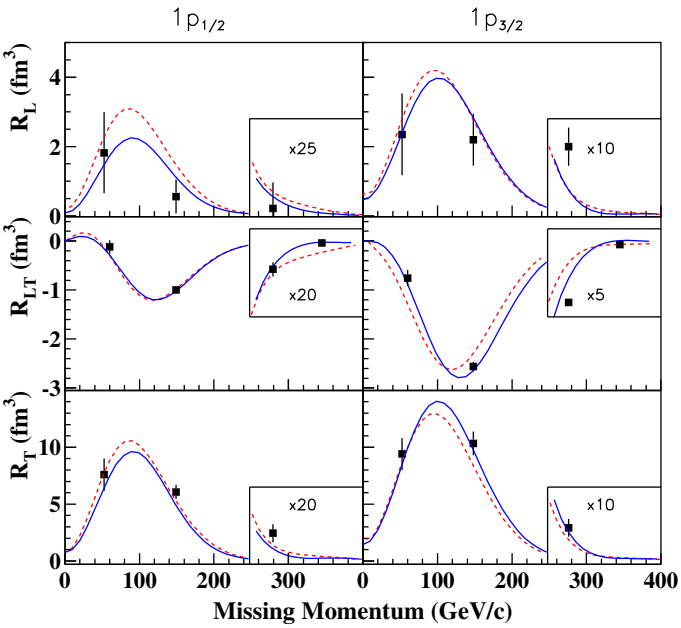

FIG. 4. Comparison of R_L, R_{LT} and R_T with the calculations.